The Substorm: An Introduction to the Topic in the THEMIS Era

- Primer -

Eric Donovan, University of Calgary (edonovan@ucalgary.ca)

The slides in my talk are grouped (15 themes).

1 (a&b): The most famous by-product of geospace dynamics is the aurora. Like an image on a TV screen, the aurora is a projection of magnetospheric dynamics. As a result, auroral observations are increasingly being used as a way of remote sensing the magnetosphere. Geospace studies, with investigations of the substorm being one example, often require simultaneous observations in space and of the aurora. Satellites observe the plasma physics at a specific location(s), but in many situations that point measurement must be understood as part of a multi-scale, larger dynamic inferred from 2D information about the aurora in a "magnetically conjugate" region (i.e., the magnetic field line through the satellite also passes through the observed aurora). Figure 1B illustrates that the vast majority of land under the auroral zone is in Canada. This "Canadian advantage" provides a view into geospace that is unique in the world, something we have capitalized on in THEMIS (and other projects).

2: The magnetosphere (and ionosphere) is a dynamic system. These dynamics arise as (a) a consequence of changes in the solar wind driver, (b) in the form of "normal modes" of the system such as ULF waves (or perhaps sawtooth events, SMCs, etc., and (c) instabilities that arise spontaneously within the system (c). The topic of this talk is the substorm, one of these instabilities, which is illustrated on slide 2c. The panel plot shows successive IMAGE WIC (near) global UV auroral images showing the beginning of the substorm onset and the expansion phase (see below). Note the onset emerges from deep within the nightside auroral zone on field lines that thread the nightside CPS (dusk is up and the sun is to the right on these images). The figure is from *Henderson et al., Annales Geophysicae,* 2009.

3: On a night in November 2004 a friend of mine – Mikko Syrjäsuo – was setting up a colour All-Sky Imager (ASI) in Athabasca, about four hours drive north of Calgary. The sky was clear and very dark, with an auroral arc (barely visible) on the southern horizon (over Montana which is unusual). Over four minutes the aurora got very bright, expanded to fill the whole sky, and became a seething and dynamic display. This was an onset – seen in person it transforms your view of the night sky (keep in mind the field of view covers well over 600 km diameter north-south and east-west and that the disturbance expands well beyond the field of view in a matter of minutes). This is the auroral "onset". I have requested that only the first (3a) and last (3c) slides in the sequence be printed out for you.

4: The substorm phenomena was named and described in the literature by *Akasofu* [*PSS,* 1964]. Slides 4b-4k illustrate seemingly disparate (but obviously interrelated) phenomena that occur around onset, and the idea of energy loading (growth phase), onset, and energy unloading (expansion phase).

5: These two slides are meant to give you an idea of several definitions of the substorm. You should know that *reasonable researchers will agree on what is and is not a substorm, but often have somewhat different definitions* (in other words do not get drawn in to long discussions/arguments about whether a particular event is a substorm – those days are over). The different definitions usually reflect personal histories focussing on different phenomena (e.g., look through slides 4b-4k and understand that researchers might spend a decade or more studying for example injections or Pi2s and that intense focus shapes their individual views of this process). All will agree the substorm involves energy storage whereby the magnetotail cannot dissipate (process) energy as fast as energy extracted from the solar

wind via dayside reconnection, and that excess stored energy is released *explosively* via an instability (which really means the system evolves to an unstable state in the growth phase). This is a cycle but is not cyclic *per se*.

6: The substorm is interesting. It is important in the geospace energy budget, is an exemplar of processes that happen throughout the cosmos, and fits into the multi-scale *complex* magnetosphere. These days, however, there are great opportunities to advance our understanding of the onset instability provided by THEMIS, and soon RBSP, together with ground-based and other (e.g., topside ionospheric satellites, Cluster, Geotail, etc.). So the substorm community is really focussed on the onset mechanism, and that is what I shall focus on here. It is *where the action is*, so to speak, these days.

7: We know from auroral observations (see e.g., *Frey et al., JGR,* 2004) that the onset is a nightside evening sector phenomena. We know from *in situ* and auroral observations that the field lines that thread the onset region are closed, and cross the neutral sheet (typically) between ~7 and ~20 Re downtail.

8: There are two paradigms within which substorm studies are typically framed. These are the Current Disruption (CD) and Near-Earth Neutral Line (NENL) paradigms (see 9), which differ in the proposed instability: for CD it's either current limiting or interchange/ballooning while for NENL it's reconnection. The question of whether specific substorms are CD or NENL has plagued our field for decades, and was the motivation for THEMIS (see *Angelopoulos, Space Sci. Rev.,* 2008). In a nutshell, CD ought to occur at the Nightside Transition Region (NTR) between highly stretched tail-like field lines and quasi-dipolar field lines, and NENL formation ought to occur deeper in the Thin Current Sheet (TCS). The former likely occurs around 7-9 Re while the latter occurs tailward of 15 Re. THEMIS is a constellation of satellites (five originally but the outer two are now ARTEMIS and are orbiting the moon). The five satellites (three with 1 sidereal days orbits, and two with 2 and 4 sidereal day orbits) are phased on their orbits so that all five would align radially during apogee every four sidereal days ("major conjunctions"), bracketing the CD and NENL regions. The alignment meridian was over Canada. The idea was to do timing, and use ground-based auroral imaging and magnetometer measurements to clarify whether the onset was on the conjunction meridian. This was revolutionary – five satellites and more than 20 ground stations designed to target the substorm onset.

9: Auroral observations have proven that the onset arc maps to the NTR, and more precisely a sharp radial transition between highly stretched tail-like and quasi-dipolar field lines (see *Lui and Burrows, GRL,* 1978; *Samson et al., GRL,* 1992; *Donovan et al., GRL,* 2008, *Sergeev et al., JGR,* 2012).

10: The fact is that the onset question has proven difficult to resolve, even with THEMIS. This is because of a number of factors… the mapping is extremely difficult, as is the timing (for things observed *in situ* because they are point measurements and for things observed in the ionosphere because of timing issues), both scenarios see the onset arc brightening very differently (in CD the onset arc brightens with the instability, while in NENL the onset arc brightens as a consequence of flow braking of a BBF that was launched many minutes earlier by the instability. There are now four (perhaps three – as I think one has now finally been disproven as a possibility) variations of the two scenarios (two each for CD and NENL – see 10g). For some examples of studies that highlight the different scenarios see *Roux et al.* [*JGR,* 1991], *Ohtani* [*JGR,* 1992], *Lui* [*JGR,* 1996], *Baker et al.* [*JGR, 1976*], *Shiokawa* [*JGR,* 1998], *Angelopoulos et al.* [*Science,* 2008], *Donovan et al.* [*GRL,* 2008], *Liang et al.* [*GRL,* 2008], *Henderson* [*Ann. Geophys.,* 2009], *Gabrielse et al.* [*JGR,* 2009], *Spanswick et al.* [*JGR,* 2010], *Kepko et al.* [*GRL,* 2010], *Nishimura et al.* [*JGR,* 2010], *Lyons et al.* [*JGR,* 2010], *Lyons et al.* [*JGR,* 2011], *Lui* [*JGR,* 2011], *Sergeev et al.* [*JGR,* 2011], *Sergeev et al.* [*JGR,* 2012].

11: I should declare[1] my bias: I am an adherent of the CD paradigm (although I like to think of it as "onset at the inner edge of the TCS" rather than "CD"), but I believe that both types occur under different circumstances. These slides give an idea of the type of evidence that has led me to this conclusion.

12: This is an extension of 11 where I focus on one event which I published in *GRL* in 2008.

13: Others are adherents of the NENL model or variants of it. These two slides are taken from the *Angelopoulos et al.* Science article [2008] presenting a very cursory summary of the evidence used to support that study.

14: I hope the talk I have prepared for the Summer School gives you a good snapshot of what is interesting and timely today – largely as a consequence of THEMIS (and associated observing programs) and the tremendous work the mission has enabled. That being said there are exciting issues that need to be addressed, and which in many cases need new missions. These slides are meant to point you in perhaps some interesting directions. For example, there is one thing every one agrees on regarding the substorm – onset starts with the brightening of an auroral arc. The fact is that we do not know what causes that arc, so we cannot say why it got brighter (see e.g., *Donovan et al.* [*GRL,* 2008])… so our one widely accepted fact is actually only marginally useful to us… we need to understand the physics of auroral arcs to understand the substorm. As well, we have never (no kidding!) measured the time series of day and nightside reconnection, so we have never measured the driver of geospace dynamics including the substorm. We need to understand the onset instability, and that is proving very difficult. We need to get a better idea of how various macro-scale magnetotail processes affect the aurora, so we can better use the auroral observations to address substorm issues. These and other issues will motivate new missions (e.g., ADEx, Kuafu) and exciting uses of data from missions that are going to be launched this year (e.g., RBSP, Swarm). *This is a very exciting time for substorm studies.*

15: Overview.

I do not expect to go through all of these slides, but will get through all sections. I have included all of this material because I hope it will prove useful to you if you are going to study substorms.

[1] For the record, you should always be aware that almost everyone in the substorm community has a view that aligns more closely with one rather than the other paradigm. I believe we are pretty good at not letting our "belief" affect our science, but there really are these two "schools of thought". Something to keep in mind when you are listening….